Development of Knowledge Retention Systems for Formula-SAE Vehicle

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The ACME Racing Team have been involved in Formula-SAE, a motorsport-based design and build competition since 2003. Due to the team's workforce issues, experience has shown knowledge is not retained effectively from one year to the next. The history and evolution of ACME Racing vehicles was analysed in order to provide future teams with critical knowledge on the development of Formula-SAE vehicles. A summary of other knowledge-related developments for the 2009 ACME Racing team provides further methods to develop knowledge within the ACME Racing team. An investigation into Australian Defence Force systems examines the feasibility of utilising these systems within the ACME Racing team. Finally recommendations for future research are discussed in order to create, retain and manage knowledge within the ACME Racing team in future years.

Contents

Introduction.................................................................................................................................1
A. Introduction.......................................................................................................................2
B. Problem Outline................................................................................................................2
C. Thesis aims and objectives..............................................................................................3
D. Thesis outline....................................................................................................................3
E. Knowledge.........................................................................................................................3
1. What is knowledge?.........................................................................................................3
2. How is knowledge managed?........................................................................................4
I. Past Work..........................................................................................................................6
A. Evolution of ACME Racing vehicles...............................................................................6
1. Introduction.......................................................................................................................6
2. Naming convention..........................................................................................................6
3. Summary of Team Involvement.......................................................................................6
4. Subsection evolution........................................................................................................10
B. Future evolution................................................................................................................20
C. 3 year plan.......................................................................................................................25
D. Current ACME Racing Knowledge Management Systems...........................................26
II. Current Work....................................................................................................................26
A. Introduction.......................................................................................................................26
B. WBS....................................................................................................................................26
C. ACME Racing Maintenance Bible..................................................................................26
D. Competition documentation............................................................................................27
E. ADF Systems....................................................................................................................28
1. Engineering hierarchy and Design Review ....................................................................28
2. Quality management........................................................................................................29
F. Lessons learnt...................................................................................................................30
1. Start early........................................................................................................................30
2. Establish a baseline, and requirements........................................................................30
3. Schedule is king..............................................................................................................30
4. Planning..........................................................................................................................30
5. Training is vital...............................................................................................................30
6. Don't be afraid to make sacrifices................................................................................30

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Introduction

A. ACME Racing Team

Formula SAE (FSAE) is an international design and build competition. The competition is aimed at University students, and requires them to produce a small, open-wheel race car. ACME Racing (the team) is the University of New South Wales at the Australian Defence Force Academy (UNSW@ADFA) entry. The team have been involved in FSAE since 2003, and have produced 4 cars to date. A summary of the team is in section II.

Traditionally, teams begin design of an FSAE vehicle at the start of the Academic year, drawing on research or development from previous years. Construction begins around May, if not earlier, and the vehicle complete by November to allow to test and evaluation. At the start of a new academic year, the team face many challenges just in getting skills and knowledge back to the standard from the previous year. Many things are often 're-learnt', and combined with the influx of new and inexperienced team members who require training, it is believed that too much time is spent re-learning and training, and that these functions can be successfully integrated into other team activities.

Team members are usually involved with the team for a period of four consecutive years, before they graduate and further their careers in the Australian Defence Force (ADF). From experience, when team members graduate, all the knowledge and experience they developed through their involvement with FSAE is lost.

B. Problem Outline

The ACME Racing team have endured a turbulent workforce since the team's inception. This has resulted in significant wasted time and effort at the beginning of each year learning the same things that the team's predecessors did in the previous year. There are three prime reasons for the turbulent workforce:

- At the end of each year, 4th year team members graduate from ADFA, and due to service commitments are unable to be involved with the project without taking further study at ADFA;
- Military commitments result in some members being unavailable of periods up to 6 weeks throughout the year; and
- The additional pressure placed upon team members by involvement at times has a detrimental effect on academic studies, resulting in some team members withdrawing all involvement in the middle of the academic year.

As a result of this, goals and schedules (if established) are never achieved or followed, and technological innovation is limited as team members are required to learn and understand essential concepts which they should be expected to already know.

The team have never placed high emphasis on knowledge management, however when the team lost a significant amount of experienced members in 2008, the importance of good knowledge management was realised.
C. Thesis aims and objectives

The overall aim of this research is to establish a system to eliminate, or at least reduce the consequences of the above problems occurring. The research portrayed in this thesis has four main aims to assist in achieving the overall aim.

The first is to develop an understanding of knowledge from an organisational perspective and the mechanisms and procedures for effective transfer, retention and management of said knowledge.

The second aim is to codify the evolution of the ACME Racing vehicles, and relate previous work on the vehicles to the design of contemporary vehicles.

The third aim of this research is to develop knowledge and management literature based on experience in managing the 2009 ACME Racing team.

The final aim is to examine Australian Defence Force (ADF) systems to evaluate the feasibility of implementing a similar system within the ACME Racing Team.

D. Thesis outline

This thesis is arranged in what can be considered a loose chronological order. The concept of knowledge management is not often discussed at an undergraduate level, so the literature review contains a summary of many of the important concepts which will be discussed.

The next three sections are split into three time domains: past, present and future. Respectively, they: demonstrate the evolution of previous vehicles and the work behind each, examine processes and systems that have been evaluated in an attempt to improve knowledge management within the ACME Racing Team, and provide recommendations for future work.

E. Knowledge

1. What is knowledge?

   Definition. Definitions of the term 'knowledge' abound (Bender & Fish, 2000) (Alavi & Leidner, 2001) (Nonaka, 2007). In order to fully realise the potential of a well-functioning knowledge retention system, a suitable definition of the term must first be adapted. The majority of definitions follow a similar core. However, various sources tailor the definition to suit the context under which the term is applied. This does not assist in understanding the key concepts behind the idea knowledge. The following definition has been selected because it provides the necessary level of understanding to expand on key concepts and ideas, while remaining relatively succinct by itself.

   Knowledge originates in the head of an individual and builds on information that is transformed and enriched by personal experience, beliefs and values with decision and action-relevant meaning. It is information interpreted by the individual and applied to the purpose for which it is needed. The knowledge formed by an individual will differ from another person receiving the same information. Knowledge is the mental state of ideas, facts, concepts, data and techniques, recorded in an individual's memory. (Bender & Fish, 2000)

   There are a number of key statements that can be drawn from this definition:

   • Knowledge “builds on information”, and for an individual to be knowledgeable, they must first possess, or have access to, the relevant information.

   • Information is developed into knowledge through “personal experience, beliefs and values”. The personal experience is a vital component separating knowledge from information (especially in an engineering environment), as an individual should not be expected to develop suitable opinions from a purely theoretical point of view (Nonaka, 2007). From experience, this is often unfortunately the case – mainly for practicality reasons. As the 2009 team discovered, understanding the operation of internal-combustion 4-stroke engines and theoretical engine tuning methods is not enough to produce a successful engine, nor can reading textbooks on composite materials allow a junior team member to create flawless fibreglass panels.

   Knowledge Hierarchy. The knowledge hierarchy is a graphical method of portraying the second point mentioned above. The knowledge hierarchy is referred to in most knowledge-related literature, and if not directly then conceptually (Standards Australia, 2005).
There are two aspects to the knowledge hierarchy as presented in Fig. 1: the four components within the hierarchy, and the processes and relationships between the various components.

**Data** can be seen as raw and unprocessed material, presented on various media. Engineering formulae, material properties and engine specifications are considered examples of data.

Through the addition of meaning, understanding, relevance and purpose data is developed into information. An example of information is a torque chart, which shows how much a bolt of a given size should be tightened. Procedures and manufacturer's operating instructions are common examples of information.

**Knowledge** has already been defined as a development of information, as noted in the transforming stage in Fig 1. Personal application of the procedures or manufacturer's operating instructions will allow a person to understand what method works best, and the specific requirements to follow the instructions in a given situation mean that the individual has transformed the information into knowledge.

**Expertise** is enriched knowledge. This can only come with significant experience, and due to the relatively short timeframe and specific nature of a FSAE team, expertise does not normally apply to team members. In the history of the program, a number of individuals have developed significant expertise related to vehicle sub-systems. The problem with this is that people recognise their experience and rely on them instead of attempting to learn all they can.

The knowledge hierarchy has come under criticism in recent years, for at times simplistic and contradictory view of the relationship between knowledge, information and data. Alavi and Leidner state that "knowledge is not found in the content, structure, accuracy or utility of the supposed information or knowledge..." (Alavi & Leidner, 2001). Others believe that the hierarchy itself is incorrect, and that knowledge should be seen as the base element from which information can be produced (Tuomi, 1999). While the opinions expressed are justified and valid, there is no 'correct' definition of knowledge in this context, and each definition is as suitable as the next. The Knowledge Hierarchy presented by Bender & Fish in Fig 1 is the most common variant, and for that reason will be used and referred to in the remainder of this paper. Differences of opinion aside, the knowledge hierarchy identifies and reinforces the belief that knowledge cannot exist outside an individual, and that it is important to understand that facets of knowledge (interpretation, retention, and application) vary drastically between individuals.

**Knowledge Dimensions.** The view that knowledge cannot exist outside an individual is not entirely correct, otherwise the term 'organisational knowledge' could be classified as an oxymoron. In order to expand and further understand the idea of knowledge, it has been split into two dimensions: tacit and explicit. These dimensions were first used by Nonaka in 1990 however similar ideas have been presented since the 1960's (Polanyi, 1962).

As with other aspects of knowledge, the near-dichotomy of tacit and explicit knowledge dimensions is but one model. Other research has expanded on the two dimensions, and produced a list of 30 odd knowledge dimensions. (Various sources, cited in Alavi & Leidner, 2001). At the level of this research, little is achieved by breaking the dimensions down in this manner. They do not appear to add any further meaning or understanding to the idea of knowledge, but merely categorise different media and forms of data, information and knowledge.

**Tacit knowledge.** Tacit knowledge is personal and hard to codify. Nonaka describes it as the know-how, such as ideas and thoughts (Nonaka, 1997).

**Explicit knowledge.** Explicit knowledge is codified knowledge. It is 'formal and systemic' (Nonaka, 1997). There is a significant difference between explicit knowledge and information, despite the fact that they are often codified in similar media. As previously mentioned, there is more depth to knowledge, and the nature of knowledge makes it much more valuable.

2. How is knowledge managed?

Organisational knowledge is not a new concept, having been around for the best part of a century (Alavi & Leidner, 2001). In recent years, however, the management of knowledge withing organisations has become a pivotal component in a company's strategy – good management provides a significant advantage, while (as
demonstrated in the ACME Racing team's history) poor management can prove to be significantly detrimental (Farmilo, 2004). Knowledge Management as a discipline is relatively new compared to other related disciplines such as project management (Bender & Fish, 2000).

An Australian Standard for knowledge management was published in 2005 – AS5037-2005 Knowledge Management – a Guide. Compared to other standards, it is completely different due to the unquantifiable nature of knowledge management (Standards Australia, 2005). This is because knowledge management requires a different approach for every organisation in order to be successful. Regardless of the unique nature of the final specific methodology, a system for knowledge management has four phases:

1. Creation / construction;
2. Storage/retrieval;
3. Transfer; and
4. Application.

These four phases serve as the framework for the development of a knowledge management system.

1. Knowledge Creation

As previously described, knowledge is created by transforming information. Nonaka recognised that knowledge is created in different ways. Figure 2 (adapted from Nonaka, 2007) demonstrates the four modes of knowledge creation.

The four knowledge creation modes are 'highly independent and intertwined.' (Alavi & Leidner, 2001). They do not (and should not) operate in isolation, just as tacit and explicit knowledge can not be used in isolation.

Externalisation. The act of codifying knowledge is externalisation. A thesis written as a summary of the knowledge developed as part of a design & build project is a perfect example of externalisation. This is the most important aspect of knowledge creation for the ACME Racing team, because it has been overlooked more than the other modes in the past.

Internalisation. The ACME Racing team have significant internalised knowledge, thanks in part to the academic studies as part of the Bachelor's degrees taught at UNSW@ADFA. Internalisation represents the act of reading a thesis, textbook, or other codified knowledge, and interpreting the explicit knowledge contained within.

Socialisation. While ACME Racing have been involved in FSAE, the socialisation mode of knowledge creation has been used somewhat through hands-on training, group discussions, and other social methods. For 2009, processes have been developed to improve the amount of socialisation within the team. Examples of socialisation for knowledge creation include apprenticeships, collective brainstorming, and hands-on workshops.

Combination. The combination mode is not usually represented by a dedicated process or method. It is often used as a combination of other modes. One application where combination is used, however, is in the creation of an academic thesis, where multiple explicit knowledge sources are studied, referenced and the knowledge within merged into a single piece.

![Knowledge Creation Modes](image)

**Figure 2. Knowledge Creation Modes (Adapted from Nonaka, 2007)**

2. Knowledge Storage / retrieval

There are various methods and systems readily available for knowledge storage and retrieval, termed 'organisational memory' (Alavi & Leidner, 2001). Systems include:
• Electronic databases,
• Codified human knowledge in expert systems,
• Documented procedures and processes, and
• Tacit knowledge within individuals and organisations.

3. Knowledge Transfer

It is not good enough for knowledge to be stored and then ignored, which has often been the case with the current ACME racing system. A positive mechanism to ensure that other team members are aware of the existence (at a bare minimum) of the specific knowledge will likely prove advantageous. There are five elements to knowledge transfer in an organisation:

1. Perceived value of the knowledge,
2. Willingness to share the knowledge,
3. Existence and efficiency of the transfer mechanism,
4. Willingness to receive the knowledge, and
5. Absorptive capacity of the receiver.

(Various sources, cited in Alavi & Leidner, 2001)

Items 1, 2, and 4 are clearly related to the knowledge culture within a team or organisation. Item 5 is beyond the scope of this research. Item 3 is often the focus of knowledge management literature, as these form the crux of the knowledge transfer phase. A number of options will be examined, but as with most knowledge management systems, cannot be easily evaluated.

4. Knowledge Application

The knowledge application phase, although self-explanatory, can be considered one of the most important components of a knowledge management system. Incorrect application of knowledge renders the entire management process useless.

A common example of organisation knowledge is the 'best practice' concept. Through experience, knowledge of a process or task is developed in an individual. The tacit knowledge can be codified as a directive or set of instructions. If the knowledge is incorrectly applied, the effects could be disastrous. The ACME Racing team have developed knowledge on how to tighten fasteners to maximise joint strength and minimise failure. If the directives for tightening the bolts were incorrectly applied, the vehicle could potentially fail, with the potential to injure or even kill.

Use of an IT system can 'have a positive influence on knowledge application'. (Alavi & Leidner, 2001). It was originally perceived that an IT-based system provide the majority of knowledge management features, however it was soon made apparent that creation of tacit knowledge through socialisation could be used more effectively, due to the team functioning as a Community Of Interest (Standards Australia, 2005).

1. Past Work

A. Evolution of ACME Racing vehicles

1. Introduction

This section is intended to provide new team members and staff with a summary of design decisions from previous year's cars. The knowledge created by the combination method will provide a stepping-stone for team members to get involved in the design of future vehicles, and minimise the issues associated with the lack of knowledge retention on design, as seen in previous years. The list of features that make up a vehicle baseline by themselves are still useful knowledge, as too often team members do not understand the processes and even components that go into designing a car.

2. Naming convention

The ACME Racing team vehicles are all named by 'WS', followed by a two digit number. WS are the initials of the driving force behind the UNSW@ADFA FSAE entry, Dr. Warren Smith. The first four cars were numbered consecutively, starting from WS01 in 2004 to WS04 in 2007. For 2009, the ACME Racing team decided to go to a model-year based scheme, starting with WS09, the 2009 vehicle.

3. Summary of Team Involvement

ACME Racing have been involved in Formula-SAE since 2003. Below is a summary of each year from 2003-2008.
ACME Racing began producing their first car, WS01, in 2003. It was never finished, as the team did not comprehend the significant amount of work that was required to complete a car. Poor management was often cited as a reason behind the lack of success of the team (Farmilo, 2004).

WS01 was the team's first entry to the competition, completed in 2004. Despite being incredibly heavy (300kg) it performed admirably, completing all dynamic events. It provided a great baseline for the team to develop on in future years. WS01 is shown in Fig 3.

WS02 is currently the team's highest placing vehicle, scoring 3rd overall in the acceleration event of the 2005 competition. It was designed as a refinement of WS01, although it did feature a number of new additions, including the signature ACME Racing brake disc pattern. The suspension geometry was broadly unchanged. The driveline was taken from WS01, due to time constraints. WS02 has proven to be a reliable vehicle, and after a thorough rebuild in 2008/2009 it is still used as a driver training vehicle. WS02 is shown in Fig 4. The similarities between WS02 and WS01 are not immediately apparent, but will be examined in detail in a later section.

WS03 was a development of WS02, with a number of major updates, including electro-pneumatic shifting, improved ergonomics and a revised driveline. WS03 did not complete the endurance event, after suffering a failed suspension rod-end and clutch in consecutive heats. The developments that occurred for WS03 meant that, on paper, WS03 should have performed better than WS02. Due to a lack of resources and time, this was not the case. Towards the end of the year, many minor components of WS03 had not been designed or constructed, which led to oversized components being attached to the vehicle. The sheer number of these components eventuated in a significant amount of unwanted weight addition, and a vital shift in the vehicle's Centre of Gravity (CG). WS03 is shown in Fig 5. It had a number of features that were taken directly from WS02. Some of these features can be identified by comparing Fig 4 and Fig 5, namely the suspension design, radiator location and exhaust system.
2007. WS04 was a marked departure from previous years' cars. Some of the changes included a fully-stressed engine, dry sump lubrication system, and a planetary gear final-drive system. The lack of understanding by team members resulted in a number of failures during final testing and evaluation, and ultimately resulted in the vehicle failing at the 2007 competition. Until 2009, WS04 was ACME Racing's last car produced for the FSAE-A competition. A combination of issues resulted in the car not completing all the dynamic events, significantly costing the team points. After the 2007 competition, nearly 50% of the team members graduated from ADFA, which resulted in a significant loss of experienced personnel. A side view of WS04 is in Fig 6. It demonstrates the significant difference between WS04 and previous vehicles.

Figure 5. WS03, ACME Racing's third vehicle

2008. The team did not begin the design or construction of a new car in 2008, and did not attend the competition. A combination of financial and logistical issues meant that the team would not be able to enter, or even spectate at the event. As a result, significant design knowledge was lost, as well as motivation. The team members that were involved were primarily involved in driver training and maintenance, with minor design tasks. Further experience was lost as more team members graduated, with very little in the way of transfer of knowledge or even tasks.

2009. The team took a new approach to the design and construction of WS09, the 2009 vehicle. This was due to the lack of critical skills within the team, and in an attempt to allow team members to construct critical components in-house. The majority of major suspension components were fabricated from sheet steel, as opposed to complex NC-machined aluminium. At the time of writing, the vehicle was in the final stages of construction. The conceptual design features of WS09 will be compared to WS04 in a later section.

Figure 6. WS04, ACME Racing's fourth vehicle
# Table 1. ACME Racing Vehicle Evolution

<table>
<thead>
<tr>
<th>Component</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tyres</td>
<td>Hoosier 13&quot;</td>
<td>Avon 13&quot;</td>
<td>Avon 13&quot;</td>
<td>Hoosier 13&quot;</td>
<td>Hoosier 10&quot;</td>
</tr>
<tr>
<td>Wheels</td>
<td>OTS Formula Ford</td>
<td>13&quot; Custom centre</td>
<td>13&quot; custom centre</td>
<td>10&quot; Custom WS09</td>
<td>Change 3</td>
</tr>
<tr>
<td>Hubs</td>
<td>Machined aluminium</td>
<td>Machined aluminium</td>
<td>Machined aluminium</td>
<td>Billet Aluminium WS09</td>
<td>Change 4</td>
</tr>
<tr>
<td>Uprights</td>
<td>Solid aluminium</td>
<td>Wirecut aluminium</td>
<td>4130 Weldment</td>
<td>Machined aluminium</td>
<td>Change 5</td>
</tr>
<tr>
<td>Brakes</td>
<td>Solid discs</td>
<td>ACME Racing pattern solid</td>
<td>ACME Racing pattern Floating</td>
<td>Solid floating bored disc, 4 wheel</td>
<td></td>
</tr>
<tr>
<td>Suspension Kinematics</td>
<td>WS01 double a-arm</td>
<td>WS02 double a-arm</td>
<td>WS04 double a-arm</td>
<td>Beam</td>
<td></td>
</tr>
<tr>
<td>Control Arms</td>
<td>Weldment Tube</td>
<td>Weldment Tube</td>
<td>Weldment Tube</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Bell Cranks</td>
<td>Billet aluminium</td>
<td>Lightened 3 piece aluminium</td>
<td>Lightened 3 piece aluminium</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Shock Absorbers</td>
<td>Fox Vanilla</td>
<td>Fox Vanilla</td>
<td>Fox Vanilla</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Pedal Box</td>
<td>Aluminium billet</td>
<td>Modified OTS</td>
<td>Aluminium Weldment</td>
<td>Modified OTS Cabin adjustable</td>
<td></td>
</tr>
<tr>
<td>Steering Rack</td>
<td>Centre mount</td>
<td>Custom Floating Rack</td>
<td>Custom Floating Rack</td>
<td>Hookes / Helicopter Joint</td>
<td></td>
</tr>
<tr>
<td>Steering Wheel</td>
<td>Unknown source</td>
<td>Paradigm</td>
<td>Paradigm with paddle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chain Drive</td>
<td>Aluminium Honeycomb</td>
<td>Aluminium Honeycomb</td>
<td>Aluminium Honeycomb</td>
<td>Aluminium Honeycomb</td>
<td></td>
</tr>
<tr>
<td>Drive Shafts</td>
<td>Small dia steel</td>
<td>Thin wall large dia 4130</td>
<td>Small dia hardened 4340</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV Joints</td>
<td>Small car OTS</td>
<td>Taylor Tripods</td>
<td>Taylor Tripods</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electronics</td>
<td>Haltech E6X</td>
<td>Motec M400</td>
<td>Motec M800 &amp; SDL</td>
<td>Motec M800, SLM &amp; SDL</td>
<td></td>
</tr>
<tr>
<td>Engine</td>
<td>Suzuki GSX-R 600</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 1 shows a graphical relationship between various components on the ACME Racing vehicles. This figure is an earlier version, which was produced when parts of WS09 were not yet completely designed. The colour scheme demonstrates how the vehicles have slowly moved away from WS01's design, with significant redesign occurring for WS09. Examples of how some components have hardly changed will be examined in further detail.

4. Subsection evolution
The vehicle design has been divided into the following subsections:
- Driver interface & steering
- Suspension
- Unsprung
- Electrical
- Engine & drivetrain
- Chassis & bodywork

These subsections are used in the FSAE Cost Report event to divide the car (SAE, 2009). There are multiple ways to split the car into sections and components, the list above is the only 'official' version. Within each section, a brief summary of the major design features of each vehicle is produced in a table, and a commentary provided on key design decisions from the subsection. These subsections also provide a foundation for the WBS for design and construction activities.

**Driver Interface & Steering**
Contained in Table 2 are the key driver interface and steering components that have been featured in ACME Racing vehicles. A summary of notable features follows.

<table>
<thead>
<tr>
<th>Component</th>
<th>WS01</th>
<th>WS02</th>
<th>WS03</th>
<th>WS04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steering column and wheel design</td>
<td>Unknown wheel, single uni column, slight incline</td>
<td>Paradigm race wheel, twin 'helicopter joint' column, significant incline</td>
<td>Paradigm race wheel, 90° bevel gear box, perfectly vertical</td>
<td>Paradigm race wheel, 90° bevel gear box, mild incline</td>
</tr>
<tr>
<td>Steering rack mounting and configuration</td>
<td>High mount, outboard mount points</td>
<td>Low mount, inboard mount points. Flat mount</td>
<td>Low mount, inboard mount points. Flat mount.</td>
<td>Low mount, inboard mount points, inclined rack.</td>
</tr>
<tr>
<td>Ackermann</td>
<td>150.00%</td>
<td>150.00%</td>
<td>150.00%</td>
<td>150.00%</td>
</tr>
<tr>
<td>Shifter mechanism</td>
<td>Mechanical linkage</td>
<td>Mechanical linkage (later retrofit with electro-pneumatic system)</td>
<td>Electropneumatic, computer controlled shifting mechanism.</td>
<td>Electropneumatic, computer controlled shifting mechanism.</td>
</tr>
</tbody>
</table>

A number of issues were identified with the driver interface in WS01, for which there is minimal design documentation available. Robottom has a 2 page discussion on the packaging and development of the steering system (Robottom, 2003), and Tizard briefly covers design of the brake pedal (Tizard, 2004). The vehicle featured a high-mount steering rack, which simplified steering column design.

In WS02, the rack and mounting setup was changed significantly. Similar steering racks were used for the next two vehicles, although the reasoning behind this is unknown.

The pedalbox is a very complex mechanical system, and is often overlooked during the design of a vehicle, as evidenced by the lack of documentation for the four years. It is interesting that the team used an in-house bespoke pedalbox for WS03 in 2006, but reverted to an off-the-shelf (OTS) system for 2007.

The shifter system has also evolved, albeit slowly. For two years the team used a mechanical system, which was composed of a number of linkages and pivots similar to the configuration on the motorcycles. In 2006 an electro-pneumatic shifter was successfully integrated into WS03, and used again on WS04. The shifter had the potential to significantly decrease shift times, and therefore increase the acceleration of the vehicle. This has never been formally evaluated.

**Suspension**
A vehicle's suspension is divided into two sections, 'sprung' and 'unsprung'. Unsprung mass comprises the components in between the ground and the damper – everything on the vehicle NOT supported by the damper(s). Sprung mass refers to all components on a vehicle that ARE supported by the damper(s), which includes the chassis, bodywork, engine, etc. This section focuses on the control arms and dampers. They are not part of the 'unsprung' mass, it was decided to deal with them in this section to break up the unsprung section, however.

Correct design of a vehicle's suspension has been the subject of numerous textbooks, and much speculation. It is not possible to summarise the design of each vehicle's suspension and provide enough knowledge to be of any use – suspension design for the ACME Racing vehicles has been the subject of at least two theses (Robottom, 2003), (Glendon, 2004), with significant involvement from Postgraduate students such as Stuart Clode. They both document the development process for unequal-length double A-arm suspension systems for WS01 and WS02 respectively.

It is known that the suspension for WS03 was remarkably similar to WS02, as parts were cannibalised from WS03 to produce a replacements for WS02 in 2008. WS04 is a marked change in design of the A-arms, going to a thinner diameter tube and a machined bearing housing, to minimise bending moments being placed on A-arm components. Due to the lack of a rear chassis, the rear upper control arms had incredibly long members, that were rumoured to have been inadequate. Successful driving demonstrated that this was not the case. Despite this, it is believed that the suspension geometry is based upon that of WS02, and the work conducted by Glendon.

The damper choice has remained fairly constant throughout the period. All vehicles used Fox dampers, but WS01 used a different version to the others, based on cost (Robottom, 2003). Damper motion ratios and spring rates were selected based on historical trends in Robottom, and through further analysis in Glendon.

Given the fact that the ACME Racing vehicles WS02-WS04 have all been between 250kg and 280kg without driver, the fact that they all have similar suspension parameters is understandable. The ACME Racing team have been trying to reduce weight from the vehicles to gain a performance advantage, and have been relatively unsuccessful due to other constraints. If the team is successful in reducing the design (and actual) weight of the vehicle in future, further analysis into suspension parameters should be done, using similar methods as Robottom and Glendon.

In 2008, informal research was conducted into the feasibility of composite control arms. Tensile tests of CFRP tube / aluminium inserts and CAE design and analysis of bearing clevi was conducted, however very little was documented. The two team members involved in this evaluation will not be involved in the ACME Racing team in 2010, however to develop knowledge, as well as the vehicles, it is suggested that team members conduct further research into the use of composite components for sprung suspension in future years.

**Unsprung**

The unsprung section comprises a large number of critical components:

- Tyre,
- Wheel,
- Upright,
- Hub,
- Brake rotor,
- Brake caliper, and
- Wheel geometry and adjustment.

Table 3 summarises the design of the above components.
Table 3. Unsprung suspension comparison

<table>
<thead>
<tr>
<th>Component</th>
<th>WS01</th>
<th>WS02</th>
<th>WS03</th>
<th>WS04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tyre</td>
<td>Goodyear 13”</td>
<td>Avon 13”</td>
<td>Avon 13”</td>
<td>Hoosier 13”</td>
</tr>
<tr>
<td>Wheel</td>
<td>OTS Formula Ford</td>
<td>OTS Formula Ford</td>
<td>Custom aluminium 3 piece</td>
<td>Custom aluminium 3 piece</td>
</tr>
<tr>
<td>Upright</td>
<td>Solid aluminium</td>
<td>Lightened wirecut aluminium</td>
<td>Weldment steel</td>
<td>Lightened machined aluminium</td>
</tr>
<tr>
<td>Hub</td>
<td>Unknown</td>
<td>Machined steel</td>
<td>Machined steel</td>
<td>Integral to hub, Machined aluminium</td>
</tr>
<tr>
<td>Brake rotor</td>
<td>Solid mounted slotted disc</td>
<td>Solid mounted “ACME Racing” pattern</td>
<td>Solid mounted “ACME Racing” pattern</td>
<td>Floating “ACME Racing pattern”</td>
</tr>
<tr>
<td>Brake caliper</td>
<td>Wilwood Dynalite</td>
<td>Wilwood Dynalite</td>
<td>Wilwood Dynalite</td>
<td>Wilwood Dynalite</td>
</tr>
<tr>
<td>Wheel geometry and adjustment</td>
<td>2 deg Static Camber 5 deg Caster Adjustable camber</td>
<td>2 deg Static Camber 5 deg Caster Adjustable camber</td>
<td>2 deg Static Camber 5 deg Caster Adjustable camber and caster</td>
<td>1.5 deg Static Camber 3 deg caster Adjustable camber and caster</td>
</tr>
</tbody>
</table>

The above information was sourced through design specification sheets from previous competitions, and thesis literature. Some of the information is missing, because it was not adequately documented. WS04 underwent a number of major modifications to the unsprung geometry as a result of driveline issues. None of these were documented or recorded on the design specification sheet, so the extent of the modifications is unclear.

**Tyre choice.** Pat Clarke, a respected motorsport engineer, believes that tyre choice should be the first component decided when designing a vehicle (Clarke, 2007). For WS01, the choice was made purely on cost (Robottom, 2003). It is unclear how or why the team changed for 2005 and 2006, however Olsen discussed the effect of tyre choice on vehicle performance (Olsen, 2007).

**Wheels.** The wheels for the first two vehicles were purchased, instead of manufactured in-house. The original design for WS03 was not ideal, and resulted in galling of the billet wheel centres. These were modified for WS04, which used an unusual mounting system to prevent damage to the wheel centres. Very little documentation for the design of the wheels is available. Figure 7 shows WS03’s tyre and wheel combination.
Uprights. The original uprights for WS01 were designed with packaging as the prime concern (Robottom, 2003). Very little analysis was done, and as a result they were incredibly bulky compared to later years. Tizard evaluated the design using FEA software (ANSYS) and significantly reduced the weight through scripted pocketing (Tizard, 2004). For WS03 the uprights were bent 4130 weldment design. Monocoque structures are very light and of high strength (Tizard, 2004), however significantly more work is involved in construction, to minimise distortion during welding.

WS04 had billet aluminium uprights, that had been significantly lightened through through-thickness pocketing. The uprights looked well designed and constructed, and were comparatively light. They included a caliper mount, increasing stiffness of the unsprung mass assembly. Very little documentation is available for these uprights, besides the CAE files.

Hub. The hub connects the wheel to the brake disc on the front wheels, and to the driveshafts on the rear (for a rear drive vehicle). Despite the fact that the hubs play a critical role in transferring torque from the engine to the wheels, they are considered an 'unsprung' component.

WS01’s hubs were developed using the same iterative process as the uprights (Tizard, 2004). A similar shape and construction has been used throughout the life of the ACME Racing team, with minor changes along the way. For WS01 – WS03, the hubs were mounted on a steel stub axle. WS04 integrated the hubs and axle assembly into one item.

Brake rotor. WS01’s brakes were chosen by determining the maximum possible size based on wheel and caliper selection. WS02 saw the first lightweight pattern for a brake disc, which was a unique feature in 2005. The discs were solidly mounted to the hub, which resulted in warped discs in 2005 and 2006, due to the rapid heat-cycling of the rotors. This was alleviated in 2007 by floating the discs on bobbins. The bobbins were secured using circlips, however it was found that during the competition the circlips were not adequately supporting the rotor, and disloging from the vehicle. This could have resulted in a potentially dangerous situation but luckily this never eventuated.

Brake caliper. The brake caliper sizing determines a number of parameters, and selection is critical to ensuring the vehicle is able to stop as required. As minimising unsprung weight is critical to vehicle performance, a lightweight caliper must be chosen. The Wilwood Dynalite was chosen in 2003, and was used until 2007 as it satisfied the vehicle performance requirements.

Wheel geometry and adjustment. While a vehicle may perform well on paper, nothing can compare to real world testing and evaluation 'I think an awful amount of time can be wasted trying to prove some theoretical stuff, when some testing does it far better and is much more fun' (P. Clarke cited in Glendon, 2004). A number of figures for initial suspension configuration were chosen 'just because' or based only on historical data (Robottom, 2003), (Tizard, 2004). Drivers have commented on the predictable nature of WS02’s handling, which demonstrates the effectiveness of the simulation and calculation performed in later work, such as Glendon.

Despite methods to eliminate construction of components deviating from designs, the fact that the majority of suspension components were welded means that warping is inevitable. Being able to adjust the suspension parameters is vital to ensuring the vehicle performs reliably. Very little time has been spent evaluating vehicle
performance and altering suspension configurations to maximise acceleration (both lateral and longitudinal). The adjustability afforded by the suspension design has mainly been used to set ‘baseline’ suspension geometry, such as the camber and caster angles as detailed above, as well as weight balance and vehicle ride height, all of which determine key performance aspects of the vehicle (Glendon, 2004), (Tizard, 2004), (Robottom, 2003).

All vehicles have possessed a similar level of adjustability. It should be noted that the steel weldment design for WS03 meant that some parameters were not as easily adjusted as they would have been on a billet upright, with bolt on clevis or bearing housings. This sacrifice was made in an attempt to reduce the weight of the unsprung assembly. Figure 8 shows the difference in upright design between WS02 and WS03. The bolt-on clevis bracket on WS02 is removable to allow installation of shims.

**Figure 8.**

a. (Left) WS03 upright showing welded, non-adjustable clevis.

b. (Right) WS02 upright showing removable, adjustable clevis.

**Electrical**

A summary of the electrical system characteristics is provided in Table 4, below. Most of the knowledge presented in this table is based primarily through experience of the various systems and discussion with past team members.

The following electrical system design criteria will be evaluated:

- ECU
- Performance sensors
- Datalogging
- Dash
- Notable features
- Electronics box location
With two exceptions (WS01 and WS09) all electrical wiring was completed by Mr. Neil Trama, a member of UNSW@ADFA staff. Very little can be said about the electrical system in terms of wire routing or gauge, which are potential sources of weight reduction and reliability. The skills required to safely and effectively wire a competition vehicle can not be easily 'learnt' through reading a textbook, and Mr. Trama suggested that the quality of wiring from WS02-WS04 improved significantly as he gained experience and knowledge of the vehicle-specific electrical system.

**ECU.** The factory Suzuki ECU could not be used, as the engine configuration was significantly different to that of the motorbike. The emissions equipment was removed, the 20mm restrictor in the intake and custom exhaust manifold as well as the wiring configuration resulted in the engine not being able to function adequately (Groat, 2003). A Haltech system was originally chosen due to the cost and assumed performance potential. The team initially had a lot of trouble getting the engine to start with the Haltech, because of electrical noise near critical sensors. Knowledge contributed by School technical staff (P. Giljevic) allowed engine development to begin in 2004 (Elmer, 2004).

The Haltech provided enough functionality to get the car to the competition, however the engine did not perform admirably. When Mr. Trama arrived at ADFA in 2005, he suggested the switch to MoTeC as he had already developed significant knowledge of the MoTeC systems through private ventures. Not only did the familiarity with the system allow ease of further development, the MoTeC systems offered additional support and functionality. So far, ACME Racing have not destroyed any engine through tuning or development, however have lost engines through unfamiliarity with the platform and poorly designed engine systems – in 2007 an engine was destroyed when rocks were allowed into the combustion chambers for example.

**Performance sensors & datalogging.** WS01 was not fitted with any datalogging equipment, so there was no requirement for performance sensors to be included as they would add weight and not offer additional performance benefits. In 2005, WS02 was fitted with wheel speed sensors only. WS03 and WS04 added additional sensors to monitor both the vehicle performance, and the driver skill. Combined with the MoTeC SDL, which offers significant datalogging capability, these sensors were used to improve vehicle performance, and also provided a baseline for structural analysis. The accelerometers are an integral part of the MoTeC ECU, and have proved invaluable over the years.

**Dash.** The first ACME Racing dash was designed to be functional and minimalistic. Figure 9 shows a prototype of WS01's dash. The isolation switch is to the left of the dash, shift light to the right and various idiot lights in between. The starter button is situated in the bottom-centre of the dash. The functions of the idiot lights and other buttons not mentioned is unknown.
Other features. The shift to MoTeC systems in WS02 allowed the ACME Racing team to experiment with a variety of performance features, including traction control, and electro-pneumatic shifting. The MoTeC computers are capable of much more, but additional features often come at a cost. The benefit of other features is either zero (many of them are only used on turbocharged engines), or the time taken to design systems to make use of the features would likely be significant.

Electronics box location. All of ACME Racing's cars have had a forward mounted electronics box, just forward of the front roll hoop. As the majority of the wiring must travel from battery (mounted under the seat), forward to the ECU and support electronics, and then aft to the engine, a large amount of weight is added by the long wires.

Engine & Drivetrain

Engine and drivetrain are possibly the most consistently researched sections of the ACME Racing vehicles, with thesis research conducted every year from 2003 until 2008. The engine and drivetrain have a number of driving parameters, as well as performance parameters. The list and table below include a combination of parameters. It should be noted that there are many more that could be included, but for the sake of expediency they are not.

- Engine selection
- Intake manifold
- Restrictor & throttlebody
- Exhaust manifold
- Lubrication system
- Cooling system
- Ignition system
- Fuel system
- Final drive ratio
- Differential
- Driveshafts
- Universal joint
- Chain tension adjustment

Key design parameters for the engine and drivetrain are further detailed in Table 5.
### Table 5. Engine & driveline comparison

<table>
<thead>
<tr>
<th>Component</th>
<th>WS01</th>
<th>WS02</th>
<th>WS03</th>
<th>WS04</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intake manifold</strong></td>
<td>Aluminium weldment side feed equal length runners</td>
<td>Aluminium weldment side feed equal length runners</td>
<td>RP nylon centre feed equal length runners</td>
<td>RP nylon side feed equal length runners</td>
</tr>
<tr>
<td><strong>Exhaust manifold</strong></td>
<td>4 into 1</td>
<td>4 into 1</td>
<td>4 into 2 into 1</td>
<td>4 into 2 into 1</td>
</tr>
<tr>
<td><strong>Lubrication system</strong></td>
<td>Stock</td>
<td>Shallow sump</td>
<td>Shallow sump</td>
<td>Dry sump</td>
</tr>
<tr>
<td><strong>Cooling system</strong></td>
<td>Stock, high mount automotive radiator</td>
<td>Stock, high mount automotive radiator</td>
<td>Stock, high mount racing aluminium radiator</td>
<td>Electric water pump, side mounted racing aluminium radiator</td>
</tr>
<tr>
<td><strong>Ignition system</strong></td>
<td>2 coil wasted spark with Haltech interface</td>
<td>2 coil wasted spark direct connection to MoTeC</td>
<td>2 coil wasted spark direct connection to MoTeC</td>
<td>2 coil wasted spark direct connection to MoTeC</td>
</tr>
<tr>
<td><strong>Fuel system</strong></td>
<td>Unknown</td>
<td>External pump, returnless rail horizontal filler</td>
<td>In-tank pump, 'traditional' fuel rail vertical filler</td>
<td>In-tank pump, 'traditional' fuel rail vertical filler</td>
</tr>
<tr>
<td><strong>Final drive ratio</strong></td>
<td>4.36:1</td>
<td>4.00:1</td>
<td>3.00:4.23:1</td>
<td>4.42:1</td>
</tr>
<tr>
<td><strong>Differential</strong></td>
<td>Audi Torsen</td>
<td>Audi Torsen</td>
<td>Formula Student Torsen, lightweight housing</td>
<td>Formula Student Torsen / Spool</td>
</tr>
<tr>
<td><strong>Driveshafts</strong></td>
<td>Assumed modified VW modified</td>
<td>VW modified</td>
<td>2” thinwall 4130 steel</td>
<td>Approx 3/4” 4340 hardened steel</td>
</tr>
<tr>
<td><strong>Universal joints</strong></td>
<td>VW CV</td>
<td>VW CV</td>
<td>Hooke's Source unknown</td>
<td>Taylor Race Tripods</td>
</tr>
<tr>
<td><strong>Chain tension adjustment</strong></td>
<td>Sliding / friction bolt</td>
<td>Sliding / friction bolt</td>
<td>Turnbuckle</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Engine.** According to Goat, the Suzuki GSX-R600 engine was chosen for value-for-money compared to the more common CBR-600 (Groat, 2003). Regardless of how the decision was made, the ACME Racing team have stuck with the same engine, and have invested significant resources in improving the engine performance. Internal modifications result in minimal gains, so the performance gains are primarily created by the two manifolds – the intake and exhaust manifold, and tuning on the School-owned hub dynamometer.

In 2005, Natano examined variable cam timing gears to determine whether the engine could produce more power than with the camshaft in the factory timing. The results of this thesis were that the engine produced the most usable (in terms of raw amount as well as peak RPM) power and torque with the camshaft at the factory timing location, further reinforcing the view that the engines are well developed at the factory, and effort is better spent examining external components to gain performance (Natano, 2005).

**Intake and restrictor.** The intake manifold and 20mm restrictor have evolved with each ACME Racing vehicle. The initial sizing was performed by Groat in 2003, and developed into WS01 and WS02’s manifold by Elmer in 2004. The aluminium intake used for WS02 is a favourite with team members for the 'roar' developed at full throttle. It is believed that it is due to resonance causing vibrations within the aluminium intake runners – the runners are comprised of aluminium tube with rubber sections to allow for adjustment of length.

WS03’s intake was the subject of further development by Pearce in 2006. Pearce tested under real world conditions and found that the intake manifold design was not optimal for the engine performance. The manifold was modified to better match the engine characteristics, and the restrictor was increased to 20mm to improve the airflow through the engine. The results of this modification were significant gains in power and torque, and the team continued to use this configuration for future vehicles.
conditions on the dyro, and developed the intake manifold for WS03. It was constructed using sintered nylon by a sponsor. Pearce also examined a variable length intake manifold, however it was never installed to a vehicle.

WS04's intake used a similar design to WS03's, however had a side-feed for packaging, and a ribbed plenum to minimise flex under high vacuum, as witnessed on WS03.

The sintered nylon manifolds can be produced with a turn around time of approximately 1 week, so considerable time can be spent developing a manifold for that year's car without worrying about not having it done on time. They are not without significant flaws, and it is believed the rough surface finish (a natural result of the manufacturing process) could contribute to a significant loss of power.

Porter conducted further research into intake manifold design, and developed another manifold design that addressed the flaws associated with WS04's design (Porter, 2008). This design was not used on a vehicle as no vehicle was constructed in 2008.

**Exhaust manifold.** The various manifold designs for 4 and 8 cylinder engines have been the subject of much debate and conjecture. Elmer examined exhaust manifold designs in 2004, however does not cite any references when comparing manifold designs. As of 2009, no formal research has been conducted into exhaust design, for numerous perceived reasons:

- The lack of space between the engine and firewall often means that the exhaust manifold design is compromised regardless of design and construction.
- The complex shape means that manifolds are very expensive to produce, so it would be difficult to create more than one for a given platform.
- Variance in 'optimal' solutions provided by different sources results in further variables to evaluate.

**Lubrication system.** Very little thought has been paid to the lubrication system of WS01-WS03. In a motorcycle, as it leans into the corner, the centripetal force acts down the centreline of the motorcycle, or more precisely from the contact patch (tyre is near hemispherical) and through the CG. As such, the oil does not ‘slosh’ in the sump, as it would in a car experiencing lateral (sideways) acceleration. The sump was shortened in WS02 and WS03 to allow the team to lower the engine, and provide significant change in design CG height of the car. This resulted in oil starvation destroying an engine in 2006. Pace believes that sustained cornering does not cause the drop in oil pressure, rather it is from the alternating accelerations as found in a slalom. Slalom sections are very common on FSAE tracks, so the issue was required to be addressed to ensure longevity of the vehicle under competition conditions (Pace, 2007).

WS04 had a dry sump system, designed by Pace. The dry sump system integrated many components, and had a number of innovative features:

- The scavenge pump was powered by the water pump drive, which allowed the team to use an electric water pump
- The structural sump plate provided mounts for the suspension, and engine to the chassis.

The dry sump system was effective for a first attempt. Issues concerning the cost of the system (the pump itself cost hundreds of US$) (Pace, 2007), the added complexity compared to a wet sump system, and questionable weight saving effectiveness meant that the dry sump was not evaluated further.

**Cooling system.** WS01-WS03 used a similar configuration for the cooling system, with the radiator mounted high, and rearward of the driver. This position raised the CG of the vehicle, and placed the radiator behind the intake manifold and driver's head, significantly restricting ram airflow that would aid in cooling.

In 2008, WS02 overheated during driver training because the thermo fan failed. The vehicle was moving at speed for extended periods. This demonstrates how little air was flowing over the radiator, and reinforced the opinion that a side mounted radiator, such as the one seen on WS04, would provide more effective cooling. The side mount (ducted or otherwise) is exposed to more airflow and will reduce the chance of the engine over heating.

The dry sump design for WS04 meant that an alternative water pump be used. Pace did not cover any cooling system design features during the design and integration of the dry sump. A Davies Craig pump was chosen, and used effectively for WS04. Research by Jiar in 2008 attempted to determine whether the flow rate of the chosen pump was adequate to keep engine temperature in check, however the outcomes of this are not clear.

As part of the competition rules, teams must have catch tanks for all engine fluids – oil and coolant. In previous years these tanks were simply modified drink bottles, chosen for price, availability, and effectiveness.

**Fuel system.** The fuel system for ACME Racing vehicles has never been the subject of detailed research or design. While some designs have been produced as a result of undergraduate course work, they are often incomplete and require significant rework to ensure they integrate to the platform. The fundamentals of electronic fuel injection (EFI) system design were included in Groat (2003), however decisions regarding the components used appear to be arbitrary. In 2006, the team switched to an in-take pump, which is smaller and lighter than the previous Bosch pumps (which are versions of the “044” motorsport pump) to improve packaging.

The team has traditionally had problems with the fuel tank foam used to manage fuel surge. As part of
scrutineer at the competition, the vehicle is filled with fuel and taken to a tilt test rig. After being raised to 60 degrees, it is lowered and the fuel level checked using a sight gauge. The foam used by ACME Racing acts like a sponge, and absorbs the fuel to prevent it from sloshing and uncovering the pickup, which is similar to oil surge (Pace, 2006). As the tilt test takes a number of minutes, the foam absorbs a small amount of fuel, resulting in a perceived leak as the level drops when the vehicle is returned to level.

Fuel is only one method that can be used to prevent fuel surge, but is very common in race cars as an external surge tank is too bulky.

**Final drive ratio.** The final drive ratio has changed slightly from WS01 to WS04. Numerical analysis concluded that the final drive for WS01 was inadequate to support rapid acceleration, so it was changed to 4.0:1 (Scott, 2005). The validity of this modification is questionable, as Scott states that changing the final drive from 4.36:1 to 4.1 that the engine RPM will be higher for a given ground speed, where the opposite is actually the case.

In 2007, Olsen researched transmission design for the ACME Racing team. The transmission integrated the final drive, differential and a significantly modified Suzuki GSX-R600 gearbox into one unit (Olsen, 2007). WS04, the 2007 vehicle, also featured an innovative planetary gear reduction. It is believed that the final drive ratio for WS04 was a result of research conducted by Olsen, but there is no evidence to suggest that this was the case.

**Differential.** The differential choice will have a significant effect on FSAE vehicle performance, predominantly because the tracks focus on tight manoeuvring as opposed to outright speed. It is during cornering that differential choice has a significant effect (Scott, 2005). The differential for WS01 was a Torsen, taken from an Audi. The same unit was used for WS02 as a lack of time and resources meant the design was unable to be altered.

WS03 used the Formula Student Torsen, which is a smaller, lighter version of the Audi Torsen unit. It used a custom designed aluminum housing, based upon work by Scott. WS04 used the same Formula Student differential unit, integrated with the epicyclic gear train. To allow further weight savings, the Torsen carrier was redesigned. A similar design to the one initially used in WS04 is presented by Olsen (2007).

During test and evaluation of the innovative driveline used in WS04, a number of failures resulted in destruction of the Torsen differential unit. It was replaced (at very short notice) by a spool. Competition drivers believed that the vehicle still handled very well with the spool. Further research into differential choice could potentially provide both weight reduction and performance increases to the team.

**Driveshafts and universal joints.** ACME Racing vehicle driveshafts have changed between WS01 and WS04. Again, very little formal research has been conducted into driveshaft design, with most designs being based off OTS equipment, designed for road cars (in the case of WS01 and WS02) or race cars (WS04). WS03 utilised a unique driveshaft system, with four hook's joints mounted to a large diameter thinwall steel tube. A welded hook's joint does not have any mechanism for extension and compression of the joint, so the differential and inboard splines were designed to accommodate this movement.

The design used by WS04 is the lightest, and stronger than other methods due to the hardened 4340 driveshafts. The Taylor Race tripods are not true CV joints, as when operating at an angle, they do produce a variable angular velocity as hook's joints do. The benefit provided by the light weight and integration of the tripod into the rear hubs is believed to outweigh the slight non-linearity of the tripod configuration.

**Chain tensioning mechanism.** As the majority of ACME Racing vehicles use a chain, some method must be devised to allow for chain tension adjustment. WS01 and WS02 used a series of bolts clamping the differential mounts to the chassis. The entire differential assembly could then slide fore and aft, providing a method to adjust chain tension. Through experience, it was realised that this method was inadequate, as a significant amount of force was required to slide the differential unit. Using the bolts in friction meant that there was potential for the differential to slide forward with time, allowing the chain to lose all tension and potentially fly off.

WS03 used a turnbuckle system, where two threaded rods were used to both adjust chain tension, and the alignment of the differential. The system was markedly lighter and simpler than the WS01/WS02 configuration. An alternative design, based on the friction bolt setup was devised by Scott, but never implemented (Scott, 2005).

WS04 used an epicyclic gear drive, which did not require any adjusting.

Due to the success and ease of adjustment of the WS03 turnbuckle-style differential, the turnbuckles were adapted for WS02 in late 2008 as part of test and evaluation for future ACME Racing vehicles.
Chassis & Bodywork

Chassis.

'The chassis is just a big bracket that holds all the other systems together.' Most inexperienced teams attempt to design and produce a chassis before any other components are designed or integrated. The end result is a mad scramble to find room to mount critical components that were overlooked in the design process. Research into chassis design for the ACME Racing team has unfortunately fallen into that category, with many component designs forced into a compromise due to inadequate room on the chassis.

The ACME Racing chassis has been constructed out of 4130 Chromoly, as it is easy for a tradesman to weld, and possesses superior strength over a mild steel such as 1020 ERW (Coker, 2004), (Taylor, 2005), (Brick, 2006). Chassis design is a very specialised field, and just as it is impossible to characterise all the suspension parameters in the page limit of this report, the chassis designs can only be compared qualitatively while remaining succinct.

The initial design, conducted by Coker in 2004, was created with driver sizing as the primary requirement. 'Once the 2004 race chassis had been welded, the integration of the components could begin.' (Coker, 2004) Admittedly a prototype was produced before the race chassis, which required modification to fit the engine and reduce the cockpit opening. This approach to designing the chassis, while acceptable for a first attempt, caused significant problems for the team. 'Unforeseen problems did arise during the integration of the chassis. One such problem that occurred was... fixed mounting brackets in the engine bay would not allow for the engine to be easily removed.' (Coker, 2004).

The second iteration, which included development of the work conducted by Coker for WS02, as well as initial development of a chassis for WS03, was conducted by Taylor in 2005. The WS02 chassis followed a similar construction method, based on expertise offered by 3rd parties (Taylor, 2005).

Both Taylor (2005) and Brick (2006) developed and refined 2 chassis'. The first was a refinement of the chassis for the academic year, and the second was an initial design for a future chassis. Brick also expanded on recommendations by Taylor to evaluate the use of stressed-skins in a semi-monocoque design. Brick conducted significant structural analysis and produced a chassis design that was lighter, stiffer, and easier to construct than previous chassis'.

For WS04, a new approach was taken with the chassis, that resulted in significant delays in chassis construction, and a deviation from work conducted in 2006. WS04 featured a stressed engine and a rear aluminium subframe. These were designed by Carter (2006) (with assistance from Pace) and Olsen respectively. The delay in chassis design allowed a greater level of integration, but due to workload issues the subframe was not analysed and few attempts at lightening the structure were made.

The stressed engine featured in WS04 proved successful during the limited testing and competition use, and it was suggested that the concept be included in future vehicles. Due to rule changes in 2008, the WS04 chassis was no longer compatible and significant modifications were required for future cars.

Bodywork.

ACME Racing vehicles have often been criticised for their body work, both by team members, judges and 3rd parties. WS01 used a fully moulded one-piece fibreglass body, secured with Dzus fasteners. It is claimed that the bodywork was incredibly heavy, and that the Dzus fasteners were ineffective. WS02 addressed this issue by using aluminium panels that followed the chassis. It resulted in an 'angular' looking vehicle, however constrution of the bodywork was simplified. The panels were all attached with Nutserts (also known as Rivnuts). The nutserts are very effective as the panels were designed purely for aesthetics, rather than for a structural advantage. Over time, and with pressure of fast driver changes, etc, the nutserts began to wear. It was found that they can easily be cross threaded and spin, which makes bolt installation and removal near impossible, as was the case in 2008 during maintenance of WS02.

WS03 used moulded fibreglass for front and side panels, and an aluminium floorpan. The moulded fibreglass was created by laying the glass directly onto a mould placed over the chassis. Due to competition requirements for the impact attenuator, the nose was significantly larger and blunter than previous years.

WS04's bodywork was an afterthought, due to a lack of time and other issues that arose during construction. The bodywork was similar to WS02, in that the majority was aluminium moulded directly off the chassis members. The nosecone was created over an expanding foam mould, but required a large amount of bog to get the shape correct, which resulted in the nosecone being exceptionally thick, heavy, and brittle.

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1Personal conversation with Michael Olsen, February 2009
B. Future evolution

By discussing the main design features of WS01 through WS04, a plan can be established for future ACME Racing vehicles. Given that WS09 is almost complete at the time of writing, the features currently used for WS09 will be used as a baseline, rather than expanding the development of previous vehicles. The use of hindsight will be used to evaluate some of the design decisions from a knowledge-management point of view.

As part of the evolution strategy within the ACME Racing team, a 3 year plan has been developed. It is envisaged that WS09 be used as a ‘learning’ platform, where many features are not ideally designed or integrated, and refined in the 2 years following.

WS09 is compared to WS04 in Table 6. WS04 is considered to be the final evolution in the initial ACME Racing vehicle series beginning with WS01. All major differences are highlighted.

<table>
<thead>
<tr>
<th>Component</th>
<th>WS04</th>
<th>WS09</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Driver interface &amp; steering</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steering column and wheel design</td>
<td>Paradigm race wheel, 90° bevel gear box, mild incline</td>
<td>Triple 'helicopter' joint, floating column</td>
</tr>
<tr>
<td>Steering rack mounting and configuration</td>
<td>Low mount, inboard mount points, inclined rack.</td>
<td>Beam mounted, wide mount rack to minimise bump steer 180 degree bellcranks for integration</td>
</tr>
<tr>
<td>Ackermann</td>
<td>150.00%</td>
<td>150.00%</td>
</tr>
<tr>
<td>Pedalbox design</td>
<td>Modified OTS. Hydraulic push type master cylinders.</td>
<td>Welded steel monocoque. Cable clutch, push-type trunnion mounted master cylinders</td>
</tr>
<tr>
<td>Shifter mechanism</td>
<td>Electropneumatic, computer controlled shifting mechanism.</td>
<td>Computer controlled electronic solenoid</td>
</tr>
<tr>
<td><strong>Suspension</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Configuration</td>
<td>Unequal-length, non-parallel double A-arm</td>
<td>Beam Front</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DeDion Rear</td>
</tr>
<tr>
<td>Roll Bars</td>
<td>None</td>
<td>Integrated into chassis and bulkhead</td>
</tr>
<tr>
<td>Other Features</td>
<td>Peg and slot with single pivot front Watt's link with trailing arm rear</td>
<td></td>
</tr>
<tr>
<td><strong>Unsprung</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tyre</td>
<td>Hoosier 13”</td>
<td>Hoosier 10”</td>
</tr>
<tr>
<td>Wheel</td>
<td>Custom aluminium 3 piece 13”</td>
<td>Custom aluminium 3 piece 10”</td>
</tr>
<tr>
<td>Upright</td>
<td>Lightened machined aluminium</td>
<td>Lightweight machined aluminium</td>
</tr>
<tr>
<td>Hub and axle</td>
<td>Integral to hub, Machined aluminium</td>
<td>'Large dia' hub to accommodate low friction bearings</td>
</tr>
<tr>
<td>Brake rotor</td>
<td>Floating “ACME Racing pattern”</td>
<td>Solid rotor</td>
</tr>
<tr>
<td>Brake caliper</td>
<td>Wilwood Dynalite</td>
<td>Wilwood PS-1</td>
</tr>
</tbody>
</table>
### Wheel geometry and adjustment
- 1.5 deg Static Camber
- 3 deg caster
- Adjustable camber and caster
- +1 deg Static Camber. No camber change on pitch.
- 3 deg Caster

### Electronics

<table>
<thead>
<tr>
<th>ECU</th>
<th>MoTeC M800</th>
<th>MoTeC M800</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Performance sensors</th>
<th>Wheel Speed</th>
<th>Steering angle</th>
<th>Accelerometers</th>
<th>Wheel Speed</th>
<th>Accelerometers</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Datalogging</th>
<th>MoTeC SDL</th>
<th>MoTeC SDL</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Dash</th>
<th>Shift light, idiot light, isolation, starter, SDL controls, SDL, steering wheel connector</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Other notable features</th>
<th>Electric water pump MoTeC controlled shift Traction control</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Other notable features</th>
<th>Two electric water pumps MoTeC controlled shift via mechanical relays Traction control</th>
</tr>
</thead>
</table>

### Electronics box location
- Forward offset
- Rear mount

### Engine & drivetrain

<table>
<thead>
<tr>
<th>Engine selection</th>
<th>Suzuki GSX-R 600cc 4cyl 2001-2003 series</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Intake manifold</th>
<th>RP nylon side feed equal length runners</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Restrictor &amp; throttlebody</th>
<th>RP nylon. Jenvey racing T/B</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Exhaust manifold</th>
<th>4 into 2 into 1</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Lubrication system</th>
<th>Dry sump</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Cooling system</th>
<th>Electric water pump, side mounted racing aluminium radiator</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Ignition system</th>
<th>2 coil wasted spark direct connection to MoTeC</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Fuel system</th>
<th>In-tank pump, 'traditional' fuel rail vertical filler</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Final drive ratio</th>
<th>4.42:1</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Differential</th>
<th>Formula Student Torsen / Spool (Drexler clutch-pack)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Driveshafts</th>
<th>Approx 3/4&quot; 4340 hardened steel</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Universal joints</th>
<th>Taylor Race Tripods</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Chain tension adjustment</th>
<th>N/A</th>
</tr>
</thead>
</table>

### Chassis

<table>
<thead>
<tr>
<th>Chassis Configuration</th>
<th>Fully stressed engine Aluminium rear subframe</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Bodywork</th>
<th>Moulded aluminium</th>
</tr>
</thead>
</table>

It is apparent from this elementary comparison that WS09 is a marked difference from WS01-WS04. It is fitting that the name convention was changed at the beginning of 2009 as the car bears little similarity to previous vehicles.

An in-depth evaluation of the design for WS09 is beyond the scope of this research. Instead a summary of the 6 main sections, he various components within each and the knowledge-issues associated with each are summarised below.

**Driver interface and steering.** The ACME Racing team could not draw on much prior knowledge developed for the steering system. The unique design of the front beam means that the steering rack must pivot to reduce the bumpsteer (when the front wheels tend to turn to the left or right as the vehicle travels over bumps, rolls around a corner, etc). The steering system was designed from scratch using a previous iteration of the
chassis, which resulted in analysis of universal joint phasing to minimise non-linearity. The pedal box was designed based on team member's knowledge of previous pedal boxes, in an attempt to customise the box to better integrate with the ACME Racing vehicle, and using a new brake master cylinder configuration allows further knowledge creation without relying on previous estimates or undocumented data. The design brief required numerous changes to comply with the FSAE rules, to fit the new brake master cylinder system, and in an attempt to save weight and construction time. As a result, it was not feasible to utilise previous designs and modify them.

**Suspension.** WS09 utilises a novel beam front end. The beam was chosen as it reduced the chassis complexity, and allowed relatively inexperienced team members to construct the sheet metal weldments for the uprights, dampers, and steering. In doing so, it addressed one of the problems from previous years, and that was attempting to involve first years and other junior team members, developing skills but without patronising them.

The rear De-Dion is not a new concept, with the De-Dion axles used predominantly in cars in the 1960's (Longhurst, 2009). For the ACME Racing team, the De-Dion (and beam) represented a significant change in direction, and all of the knowledge developed by past members such as Glendon was not fully utilised. The geometry for the suspension, such as static angles (camber and caster) was established based on test and evaluation of the parameters used by Glendon, and through real-world testing of the ACME Racing vehicles.

The beam suspension and lack of rear chassis have dictated that direct acting dampers be utilised. The team have decided to use a more advanced damper than the Fox shocks, designed specifically for a FSAE application. The adjustability offered by these dampers will hopefully restore similar suspension rates without the use of bellcranks.

**Unsprung.** The unsprung components were designed based on WS04, however significantly modified to suit the 10" wheels and tyres. A new feature is the design on the large diameter hubs. The hub is shaped more like a 'cylinder' rather than a 'windmill'. See Fig 10. By using a larger hub and a different bearing configuration, the hubs are more efficient compared to previous years (reinforced by the failure of a hub in bending in 2007). The rear hub is also designed to support the tripod housings, with steel inserts so the 7075 aluminium is not destroyed. In 2004 the tripod housings were made out of hardened 709 steel, which greatly increased complexity and weight.

![Figure 10.](image)
a. (Left) WS04 hub with integral brake disc carrier
b. (Right) impression of WS09 hub installed inside upright

WS09's hub also features a removable brake disc carrier, which also functions as part of the bearing preload mechanism. The pocketing in the upright for WS09, as shown in Figure 11b, does not protrude through the entire upright. This significantly increased the upright stiffness, however meant that NC milling was required as opposed to wirecutting, as used on WS02.

As mentioned previously, the brake system for WS09 is a significant change from previous year's vehicles. Four wheel braking is used instead of 3 for a number of reasons:

- The change to 10" wheels required smaller brake rotors and calipers.
- Integration of 1 caliper on the rear bulkhead was quite difficult.
- The planned brake force required was inadequate with 3 brake calipers.
- The overall weight addition is negative due to the smaller mass of the rotors and calipers.

Tyre choice (Hoosier R25A compound) was made purely based on availability.

**Electrical.** Very little of the electrical system has changed from WS04 to WS09. This is because of the lack
of knowledge within the team, which is primarily due to reliance on staff from 2005-2008. The issues getting the engine to work initially reinforce the view that it is very easy for the electrical system to disable a car, with little hope of fault finding – it took close to 2 years to get the engine started and running correctly in 2003 and 2004 (Groat and Elmer respectively).

Because of chassis size restrictions, an alternative location for the electronics box was required. As mentioned during design of WS01-WS04, the majority of wiring runs from the front of the car to the rear, unnecessarily adding weight and complexity. For 2009, the exhaust was rerouted and the box placed inbetween the engine and the firewall. This location is significantly closer to the battery and the engine, which will eliminate significant weight from the vehicle and simplify fault finding through reduced noise and interference.

Less of an emphasis has been placed on datalogging and performance sensors, as they were not used to their full potential in previous years.

**Engine and drivetrain.** The ACME Racing team have stuck with the GSX-R600 engine as there has been significant knowledge of the engine developed over the years. The intake manifold was redesigned by Porter in 2008, and modified to comply with 2009 rules and chassis restrictions. The exhaust manifold was designed to be constructed inhouse using prebent mandrel bents, while the fuel system and cooling system are not significantly different from WS04.

WS04's final drive was well executed, but ultimately unsuccessful with multiple failures both before and at the FSAE competition. The decision was made in late 2008 to use a tried and tested differential assembly from Germany. The Drexler differential (Fig 11) is smaller and lighter than the Torsen differentials previously used, and has been used in multiple competitions by a number of teams. The purchase cost of this differential was offset by the amount of design, development and construction that would have occurred if the differential was to be made in house. The differential is mounted directly to the rear bulkhead, simplifying the chain tensioning mechanism and reducing the number of components that 'hang' beyond the rear of the engine.

The team have chosen to use an 11 tooth front sprocket after a manufacturer was found. The 11 tooth sprocket allows the team to use a smaller rear sprocket, decreasing the distance between the engine and the rear wheels. This will allow the CG to be shifter further rearward to improve the vehicle's performance.

The driveshafts are similar to WS04, but have been designed so they are equal in length to facilitate ease of construction.

Use of the premade differential assembly creates a number of knowledge issues for the team. Communication with the German manufacturer is not easy, and a confidentiality agreement means the inner workings of the unit are unknown. The research conducted by previous team members such as Scott (2005), Newman (2006) and Olsen (2007) into understanding the differential provides a good reference for differential design, however the knowledge developed through design, integration and hopefully operation of the Drexler should be continued in future years. A rendering of the differential assembly and bulkhead are in Fig 12.

**Chasis & Bodywork**

Rule changes in 2008 and 2009 required an all new chassis for WS09. The chassis was designed with the knowledge and experience of 2009 team members in mind. The chassis was designed and constructed in a
similar fashion to previous years, drawing on work by Coker, Taylor and Brick. The chassis was created from scratch because of the unique suspension requirements.

The rear bulkhead (Fig. 12) is used to mount the differential and jacking bar, and takes some of the rear suspension load. It also contains mounts for the Watt's link, rear anti-roll bar and brake light.

WS04 used bodywork created by moulding aluminium panels over the chassis members. This method was light and simple. For WS09, the bodywork was designed and moulded using expanding foam. As the team had not used a plug / mould method of producing fibreglass panels since the Electric vehicle, team members researched and evaluated various methods of construction the bodywork to ensure a good finish. While constructing the plugs it became apparent that producing high-quality bodywork was beyond the scope of the team members. The team had absorbed significant amounts of data and information regarding construction of moulded fibreglass panels but did not have enough knowledge and expertise to produce adequate panels by the required time.

C. 3 year plan

After analysing key design decisions for the ACME Racing vehicles WS01-WS04 and WS09, a plan suggesting the design parameters for future vehicles was developed. From a knowledge perspective:

- The plan draws on previously codified knowledge readily available to the team.
- It discourages the 'reinventing the wheel' attitude that has been prevalent.
- It promotes knowledge creation and development in junior team members.
- It is intended that the ACME Racing vehicles are not designed specifically to win the FSAE competition, but perform admirably and promote further development and refinement.

The 3 year plan is at Appendix A.

D. Current ACME Racing Knowledge Management Systems

There is one prime system currently in place within the ACME Racing team that is used for knowledge management. A shared network drive was established by the School of ACME, to provide storage of explicit knowledge for the team. The drive structure is arranged in a hierarchical manner, however after years of neglect it has not been used correctly, especially in 2008 and 2009, where inexperienced team members were constantly removing files, saving duplicate files, and ignoring the hierarchical structure that had been previously established.

Without any formalised structure or instructions, the majority of files within the drive would be considered data or information from a team perspective. As team members read manufacturer's websites, they come across a useful datasheet or similar document, and immediately save it to the drive. Without a clear description, context or at times justification, the majority of information saved to the drive is wasted. As Microsoft Windows takes a while to search through the large collection and because the hierarchical structure is not very logically arranged, the usefulness of the system in its present form is questioned.

The ACME Racing Team do not currently have any formal systems in place for tacit knowledge creation, or retention. The majority of tacit knowledge is created in junior members through a mentoring approach. While this is an accepted knowledge enabler (Standards Australia, 2005) the lack of formal structure limits the effectiveness of this method. It also does not allow for benchmarking or evaluation methods to occur, which are important aspects of developing a successful knowledge management system (Leibowitz & Megbolugbe, 2003).

II. Current Work

A. Introduction

The processes and documentation that have been created in an attempt to improve knowledge management within the ACME Racing team are summarised in this section. AS5037-2005 contains a number of 'enablers' to knowledge management. These enablers are 'tools, techniques and activities used to implement knowledge management' (Standards Australia, 2005). Other sources for these deliverables include recommendations put forward by Kurylewski from his research into application of systems engineering within the ACME Racing team (2006), and discussion in papers such as Bresnen et al (2003).

B. WBS

A work breakdown structure (WBS) is 'a product oriented family tree subdivision of the hardware, services and data required to produce the end product' (Kerzner, cited in Kurylewski, 2006). The WBS was constructed
to demonstrate to team members every component and process that goes into construction of an FSAE vehicle. Compared to work produced by Kurylewski, the WBS in Appendix B includes project management and other administrative processes that are required of a successful project.

It was originally intended to break every component of the WBS down further into individual tasks, and knowledge that is required to complete each task. It was proposed that doing this would allow a Project Manager to understand what knowledge must be developed in order to successfully manage the team, however the design of WS09 meant that there were very few specific process for construction of the vehicle.

By documenting every activity and component, it was also believed that the WBS could become the core of an IT-based knowledge management system (KMS) for the team. By definition, each WBS item must be completed in order for the team to deliver the vehicle in time for the competition at the end of each year. Each item would have associated knowledge required to complete each task or produce each component, and the hierarchical, process-oriented approach to storing the knowledge would allow ease of retrieval of only relevant knowledge. This was not examined in further detail, as a lack of time did not allow further development beyond the initial WBS. If used, the KMS would have dealt primarily with process-based knowledge, created by \textit{Externalisation} – essentially a 'lessons learnt' database, but in a hierarchial format.

\section*{C. \textbf{ACME Racing Maintenance Bible}}

The ACME Racing Maintenance Bible was originally conceived in 2008 as an attempt to codify and \textit{Externalise} the platform specific maintenance knowledge developed from 2006-2008. The Bible is still in development in 2009, as WS02 underwent significant modifications in early 2009, and because WS09 is currently in development.

Any FSAE Vehicle is produced in low enough numbers to be considered a prototype, and given ACME Racing’s relative inexperience (FSAE-Australasia began in 2000, FSAE started in the 1980's in the United States) there exists potential for components to fail unexpectedly, even with a suitable maintenance regime.

The Bible contains a development of the maintenance task lists, detailed procedures and information on the vehicles operated by ACME Racing, which at the time of writing were WS02 and WS04. After the Bible was commenced it became apparent that codification of knowledge which had been created in new team members using \textit{socialisation} – mentoring and apprenticeships – was very difficult. The amount of detail required for team members to effectively use the Bible was underestimated. As the designers and producers of many of the vehicles' components had moved on, significant research was required to ensure the procedures that had been passed down over the years were actually correct.

\textbf{Maintenance Philosophy.} As mentioned, any FSAE vehicle is a prototype vehicle by nature. Using a combination of mass-produced and one-off components means that the maintenance is different from vehicle to vehicle, however it has never been a team requirement that the designer of original components also produce suggested maintenance requirements and documentation to ensure reliable operation of the vehicle. Pace produced test and evaluation documentation for the dry sump system fitted to WS04 (Pace, 2007), but the proposed maintenance for the components was only communicated verbally.

The ACME Racing vehicles are thoroughly serviced after every drive. The components are often highly-stressed in an attempt to save weight, and so must be conditionally inspected. The majority of maintenance of these vehicles is conditionally-based. Because team members usually have little to no experience with understanding component failure, besides courses taught as part of their undergraduate degree. Not only that, but because the vehicles are only required to last for a few thousand km maximum, fatigue and failure analysis is often overlooked. As of 2009, no components have been designed to be replaced after certain intervals or periods.

Engine components should be maintained according to manufacturer's specifications, as they are essentially unchanged. Unfortunately, because the vehicles lack an odometer and are not driven as often as a motorbike would be this is not always the case. Oil and other fluids are currently replaced on a conditional basis. It has been proposed that this system be replaced with a time-based method based on analysis of historical data. Because no ACME Racing vehicles were operating for long enough during 2009, it was impossible to collect the data.

\textbf{Procedures.} As the Maintenance Bible was expanded, it quickly became apparent that other areas related to the correct operation of the vehicles should also be included in the Bible so it could function as a stand-alone document, so that team members would be able to conduct all the required processes in future years, when the team members originally responsible for design, construction and operation of the vehicles had graduated from the academy.

The Maintenance Bible currently details specific instructions and directions for maintenance activities conducted on WS02, the 2009 driver training vehicle. The bible is a living document, as vehicle configuration is constantly changing for test and evaluation of new components. As a new vehicle is produced every year, it is vital that the bible be updated to reflect the different platforms.

\textbf{Location.} The ACME Racing Maintenance Bible is currently only available in electronic form, from the
ACME Racing team office. As it is developed and utilised further, it is envisaged that the Maintenance Bible be left with the vehicles in the work area, so procedures can be referred to when required.

D. Competition documentation

The FSAE competition is not composed entirely of driving events. Close to 1/3 of the points are allocated to the static events: design, presentation and cost (Society of Automotive Engineers, 2008). Each event requires a significant contribution to achieve a decent mark. Teams with little experience often perform poorly because of the lack of understanding of each event that can only be gained through experience (Clarke, 2004).

In 2009, only two undergraduate members of the team had prior experience of a competition. It is proposed that the main team members involved in the static events are the junior team members. The more experienced ones have had other priorities throughout the year, which has dictated the increased involvement from junior members. In order to achieve the team’s goal of a top 5 finish in at least one static event, the senior team members have been mentoring the junior team members during this phase. This is equivalent to Nonaka’s Socialisation method of knowledge creation, which Bresnen et al found was more important during a study of an engineering project (2003).

Not only did the mentoring aspect create knowledge within the junior team members, but production of the documents is a form of codification, or Externalisation. They are one of the few consistent documents produced by the team from year to year, and the design documents in particular demonstrate the key design features and methodology used by the team.

E. ADF Systems

As part of a process for development of a knowledge management system for the ACME Racing team, systems used by the ADF were examined to see if they could be adapted for use by the ACME Racing team. This is not to say that the systems used by the ADF are best practice, as there is very little formalised structure that is used to transfer knowledge, especially at the end of a posting cycle.

Posting cycles. There is no clearly accessible documentation that describes how knowledge is generically transferred, created and retained in the ADF. This was quite bizarre considering the very turbulent workforce due to postings which only last 2-3 years. A number of projects have been commissioned to examine, and improve knowledge management within the Australian Defence Organisation (ADF + DMO and other civilian agencies), such as the report by Warne, Ali and Pasco (2003). Based on limited experience with ADF units as well as the DMO, there are a number of systems that have the potential to improve knowledge management within the ACME Racing team. They are: the ADF Engineering Hierarchy, and DMO's QEMS Quality Management System.

1. Engineering hierarchy and Design Review

The ADF Engineering hierarchy is comprised of three levels:

1. Design development
2. Acceptance
3. Approval

The three levels are used to review and approve designs and modifications to ADF systems. The use of the hierarchy will be examined from an Airworthiness point of view, as there is more readily available documentation compared to land or maritime systems, however they use similar systems (DI(G) LOG 4-5-015).

When a design is produced, it is subject to independent review before it is accepted. The design is then subject to a second review by a more senior engineer, before it is approved and the platform modified or constructed as necessary. ‘All engineers are human and all humans make mistakes. No matter how simple the design or how qualified and hardworking the engineer, occasionally mistakes will be made. The purpose of Design Review is to find those mistakes and correct them before a design is incorporated.’ (AAP 7001.053 Sect 3 Chap 6 Para 11)

Just as the ADF produce new systems and make modifications to current systems, the ACME Racing team produce designs and modifications for the FSAE vehicles. It is believed that implementing a formal Design Review process will forcibly retain design knowledge within the ACME Racing team.

The flowchart (Fig. 13) was adapted from AAP 7001.053, and demonstrates the application of the three tiers to producing an approved design.
How implementation of a hierarchy results in knowledge retention. At first glance, the implementation of a design review system does not appear to offer any solutions to the issues discussed in this thesis. Good knowledge management is not a direct result of the implementation of a system such as this. Instead, if the system is implemented, it would REQUIRE knowledge to be adequately managed in order for the system to correctly operate.

Firstly, the higher-level authorities who approve and accept the designs must have significant knowledge to be able to certify a design. The knowledge would have been developed through prior experience at a lower level, such as design or approval.

Secondly, use of the system implies some form of data storage in the form of logs and processes. Without historical data, Approval and Acceptance processes have no Technical Information to base decisions on. The acceptance and approval processes are as much about ensuring the component meets performance criteria as ensuring the component has been adequately designed (AAP 7001.053). This is a good practice, regardless of the systems put in place, as it will improve the design process for future cars.

Other steps required to implement a system. The team can not simply begin using such a system. Before the system is implemented, a significant investment must be made in establishing supporting systems, such as:

- Requirements breakdown structures,
- Function and performance specifications for systems, subsystems and components,
- Thorough analysis and codification of load cases and safety factors,
- Auditing processes,
- Processes for establishing Judgement of Significance (JOS),
- Certification processes for approval and acceptance members, and
- Secure storage for accountability,

Drawbacks. The Design Review process is commonly used as a means of peer-review. To establish a system within the ACME Racing team would require a significant investment, not only in setting up the support systems mentioned above, but also in implementing and operating the Design Review system. Because the ACME Racing FSAE vehicles are prototypes, over 1000 individual components are designed, analysed and integrated. Admittedly components are shared throughout the vehicle, such as the unsprung assemblies on each corner, but the time taken to adequately design these components initially requires a significant investment. Having to then have each design reviewed at least once more, while potentially beneficial in terms of performance and reliability, would place severe restrictions on an already tight schedule.

Reviewer independence is another drawback, mentioned in the AAP. Because of the small number of team members, even assuming that every team member was 'qualified' to review other designs, most designs have input from at least one other person within the team. For critical components, team members have relied on a limited number of academic staff to review designs. Unfortunately the staff also get involved in the initial

![Design Review Flowchart](Figure 12. Design Review Flowchart (Adapted from AAP 7001.053))
design of the components, which again compromises the independence of the Design Review process. Other potential sources of reviewers are technical staff, and ACME Racing alumni. Again as they are often involved in design of the components, independence is not guaranteed however their isolation from the program in general means that if suitably qualified (another issue) they could be used to review ACME Racing designs.

The Design Review process does not have any influence on knowledge management of areas other than the design. The original purpose of this research was examining tacit knowledge as skills – construction, trade skills, maintenance understanding, etc. As the Design Review process does not provide any structure for management of this knowledge, it would have to be implemented alongside other knowledge management systems. This severely limits the usefulness of the Design Review process.

2. Quality management

The Defence Materiel Organisation (DMO) are responsible for acquisition and in-service support of all ADF materiel. Major acquisition projects can take decades from start to finish – the AEW&C program was initially established in 1994/1995 (Defence Materiel Organisation, 2009) and the aircraft have not been delivered at the time of writing.

Because the projects can take such a long time, and ADF postings usually last 2-3 years, the DMO have built a Quality Management System, which can be adapted for knowledge management by the ACME Racing team. The Quality Management System is known as 'QEMS' within DMO. It appears as a tree-based hierarchy, which contains a knowledgebase for main DMO processes. Each element within the tree contains a descriptive page, with a structure containing links to references, document templates, archived project documentation, and other useful knowledge items.

The layout of the DMO QEMS can be compared to the intended application of the ACME Racing WBS – a hierarchical tree, which is navigated down to an individual process (or component in the case of construction processes). For each process or component, codified knowledge for design, construction methods, 'lessons learnt' can be readily accessed by ACME Racing Team members or project members in the case of QEMS.

Unfortunately no further information is readily available on QEMS, and screenshots and references are unable to be displayed for security classification reasons.

F. Lessons learnt

As part of developing knowledge for the team, a simple system that can be implemented in isolation is a 'lessons learnt' database. The lessons learnt are documented in chronological order, and if done correctly can provide insight into all aspects of the ACME Racing FSAE team, from management to design and construction.

Some of the lessons learnt that will be added to the database are summarised below.

1. Start early.

Every year the team attempt to start construction early, to maximise test and evaluation time at the end of the year. The project manager must keep a tight control on design and development schedules – while it may seem tempting to delay construction to allow further iteration, one week testing the entire car is much more valuable than one week delaying construction to save 0.5kg off a component.

2. Establish a baseline, and requirements.

To ensure that the first point happens, a specific set of requirements must be established for main designs (RBS). Once a component is designed to the requirements in should be considered complete and ready for production. It may not be the lightest, stiffest, or most efficient component but the evolution concept allows the component to be improved at a later date.

3. Schedule is king.

Unlike other Defence acquisition projects, the ACME Racing team has a very strict deadline – if the car is not ready by the FSAE competition than the entire project has failed. The schedule must drive EVERY aspect of the car – if a component can not be sourced or manufactured in time then it must be substituted with another component. If a design is not finalised on time then it must be modified.

4. Planning.

Team members must plan all activities, including team meetings, weeknight construction, and most critically, weekend sessions. Every weekend must have goals and objectives for progress. Not only does it provide motivation for team members, but without adequate planning, construction progresses much slower and team members lose interest.

5. Training is vital.

Very few ACME Racing team members hold formal trade qualification, which cost significant time and
money in 2009 as components and processes were outsourced at great expense. There are still many activities that can be conducted by team members besides the design of components, and there are many enabling activities that require specific skills, including:

- Dyno tuning,
- Painting,
- Bodywork plug, mould and fibreglass creation,
- Sheet metal fabrication, and
- Static event preparation.

Not only are there specific skills, but there is also specific knowledge that can be developed within the team. Again, due to lack of ethics approval the level of understanding and knowledge was never examined, but there remain subjects which require a high level of understanding, including:

- CAE design and analysis – processes, complex analyses and determination of load cases;
- Vehicle dynamics;
- Material handling; and
- School-specific procedures.

It is proposed that the team implement further training processes to ensure the tacit skills associated with the above subjects and activities are effectively transferred from year to year.

6. Don’t be afraid to make sacrifices.

During the development of WS09, a number of very expensive components were chosen as they were believed to provide superior performance over those that cost 1/10th the price (brake master cylinders). The cost of the master cylinders made up a significant proportion of the team's budget, and put restraints on other important areas. The majority of road going vehicles use a version of the cheaper master cylinders, which were initially purchased from a general auto-parts store in 2004. If the master cylinders do provide additional performance associated with the increased cost, then by all means they should be selected if it is financially viable. Given a tight budget, tight schedule and an inexperienced team (such as 2009), alternatives should have been sought and designs modified to accommodate this modification.

7. Stay in control.

When involved with a community of interest, all members are working towards a common goal. This often means that members will exercise initiative where applicable to get the job done. The project manager must still be made aware of all decisions that are made, and at all levels, so that overall control of the project is not lost. For more serious matters, the project manager must be consulted to ensure the decision does not significantly affect the schedule, budget, or even design of the vehicle. The schedule drives production, and the project manager controls the schedule. This should always be the case, the nature of the project dictates that each decision has the potential to cause significant issues for the team.

G. What was not done

As with any project, the research conducted in order to research and develop systems for the ACME Racing team was not without obstacles.

1. Team surveys

A fundamental component of this research was to develop a system that was appropriate to the ACME Racing team. It was proposed that a number of studies into how the team currently share knowledge, and how team members best learn new knowledge be conducted. Due to ethical reasons, this research was never conducted. Team surveys were created to determine the base-level of knowledge of team members, and if there was a common learning style that would most benefit the team members.

2. Conceptual system design

Throughout the year, a number of conceptual ideas for a holistic Knowledge Management System to suit the ACME Racing team were proposed. Unfortunately these were never developed into usable solutions due to a lack of support (ethics) and time.

3. Effective team management

It is proposed that a knowledge-supportive culture can be developed through effective project management. One of the aims of the WBS developed earlier was to integrate knowledge management tasks into the project and team management functions. Time must be set aside for knowledge creation and knowledge sharing (Standards Australia, 2005). Team meetings and group coaching sessions are effective knowledge enablers (Standards Australia, 2005), and while attempts were made at both, neither method was formalised, nor the
importance of each established within the team. It is proposed that future years integrate further Systems Engineering principles, as discussed in Kurylewski (2006) to improve the project management process. The management package developed by Farmilo (2004) also provides excellent guidance for project managers in future years.

4. Knowledge benchmarking
   A simple method to establish rules and requirements for a knowledge management system is through understanding what similar organisations or teams do (Liebowitz & Megbolugbe, 2003). It was initially proposed that a survey or similar mechanism be used to compare the systems in place within the ACME Racing team to other FSAE teams, however this never occurred, for the same reasons that the team surveys were not conducted.

III. Recommendations for Future Work

A. For the team
   If the ACME Racing team wants to remain successful in future years, a culture change must be effected, towards a positive knowledge sharing environment. This can be implemented by use of knowledge enablers as stand alone mechanisms, as well as Knowledge Management Systems, such as IT-based systems.
   As part II established, documented history of design, construction and management processes within the team is a simple, but effective way of transferring knowledge from one year to the next. Other methods can be found within AS5037-2005, including group coaching, and formal team meetings.
   The ACME Racing Team are encouraged to refine current systems. The main system used at the time of writing was the shared network drive. The drive's structure appears to be a 'dumping ground' for documents sourced from the internet, and work conducted by team members. A coherent structure should be developed, and content on the drive managed and maintained as the team develops and externalises more knowledge.
   It is recommended that the ACME Racing team implement a more formal Design Review process, and integrate it as part of a systems engineering approach to project management (see Kurylewski).
   If is recommended that as part of the formal Design Review process, senior team members provide measurable requirements for each major design, to ensure that time is not wasted refining a design when the gains to be had are negligible.
   It is recommended that the team implement a lessons learned database, as part of an initial stage of knowledge management system development.
   It is recommended that the team implement training processes, such as workshops and briefs, separate to on-the-job training, for all aspects of involvement with the ACME Racing team.
   It is recommended that when team members go to design a component for an FSAE vehicle, that they check to see whether any similar work has been done in the past. The knowledge contained in this report provides a quick summary of thesis research and design parameters as a reference.

B. For research
   The main aim of this research was to develop a knowledge management system for the ACME Racing team. This was not achieved, as a combination of ethics and time restrictions meant that the research deviated significantly from that which was originally proposed.
   It is recommended that future research be conducted using systems engineering principles to develop a conceptual design for a knowledge management system to suit the ACME Racing team.
   It is recommended that further research be conducted into ADF systems, including the Design Review process, and Quality Management Systems.

IV. Conclusion
   The initial aim of this research was to develop a system for managing knowledge within the ACME Racing team. This aim was not achieved, as a result of ethical, time, and other constraints. Instead, the knowledge provided within this report provides a baseline for the design and development of all the ACME Racing vehicles to date. The report also documents efforts that have been made to improve knowledge retention within the team, processes and enablers that can be used to develop a knowledge-sharing culture within the team, and provides recommendations for further research and development of knowledge management systems.
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